APPENDIX B

FUNDAMENTALS OF COMPACTION, FIELD COMPACTION TEST METHODS, AND FIELD MOISTURE-DENSITY TEST METHODS

SECTION B-1. FUNDAMENTALS OF COMPACTION

B-1. Factors Influencing compaction. Soil compaction is the act of increasing the density (unit weight) of the soil by manipulation by pressing, ramming, or vibrating the soil particles into a closer state of contact. The most important factors in soil compaction are type of soil, water content, compaction effort, and lift thickness. It is the purpose of field inspection to ensure that the proper water content, lift thickness, and compaction effort are used for each soil type so that the desired degree of compaction is obtained. When the water content, lift thickness, or compaction effort being used does not produce the desired degree of compaction, changes may be necessary. The determination of the necessary changes of these factors to produce the desired degree of compaction requires knowledge of the principles governing the compaction of soils. Therefore, it is important that inspection personnel have a general understanding of the fundamentals of compaction.

a. General. It has been established through research and construction experience that there is a maximum density to which a given soil can be compacted using a particular compaction effect. For each soil and a given compaction effort, there is a unique water content, which is called the optimum water content, that produces the maximum density. The purpose of the laboratory compaction test is to determine the variation in density of a given soil at different water contents when compacted at a particular effort or efforts. Normally, the soil to be used is compacted in the laboratory over a range of water contents using the impact compaction procedures given in MIL-STD-621A and ASTM D 1557. The compaction effort used is selected on the basis of the requirements of the structure. In foundation or backfill design for most major structures, the CE 55 (also termed modified) compaction effort that produces approximately 56,000 foot-pounds per cubic foot of compacted soil should be used.

(1) For some cohesionless soils, a greater maximum density can be obtained using vibratory-type compaction procedures given in EM 1110-2-1906 and ASTM D 2049 than can be obtained using MIL-STD-621A or ASTM D 1557 impact-compaction procedure. Thus, there may be cases where the vibratory compaction method may be more appropriate in determining the maximum density. The compaction effort used for design purposes should be the basis for construction control.

(2) A compaction curve is developed in the impact-compaction test by plotting densities (dry unit weights) as ordinates and the corresponding water contents (as percent of dry soil weight) as abscissas. For most soils the curve produced is generally parabolic in form. Figure B-1 shows a compaction curve. The water content corresponding to the peak of the curve is the optimum water content. The dry unit weight of the soil at the optimum water content is the maximum dry density. The zero air voids curve represents the relation between water content and dry density for 100 percent saturation of the particular material tested. Thus, it shows the dry density for a given water content based on the condition that all the air is forced out of the voids by the compaction process.

b. Influence of soil type. Compaction characteristics vary considerably with the type of soil. Figure B-2 shows four compaction curves representing the water content-density relation for four general soil types for standard compaction. The maximum dry density for a uniform sand occurs at about zero water content, although density approaching maximum can be obtained when the sand is saturated. A very sharp peaked curve of dry density versus water content is usually obtained for a silt, and water content is critical to achieving maximum density. A small change in water content (as small as 0.5 percentage point) above or below optimum causes a significant decrease in the density (as much as 2 to 4 pounds per cubic foot) for a given compaction effort. The compaction curve for a lean clay is not as sharp as that for the silt, and water content control is not as critical. Optimum water contents for silts and lean clays generally range between 15 and 20 percent. The compaction curve for fat clays is rather flat and water content is not particularly critical to obtaining maximum density; a 2 to 3 percentage point change in water content from optimum for fat clays causes only a small decrease (1 pound per cubic foot or less) in density. The maximum dry density, as obtained in laboratory compaction tests using MIL-STD-621A and

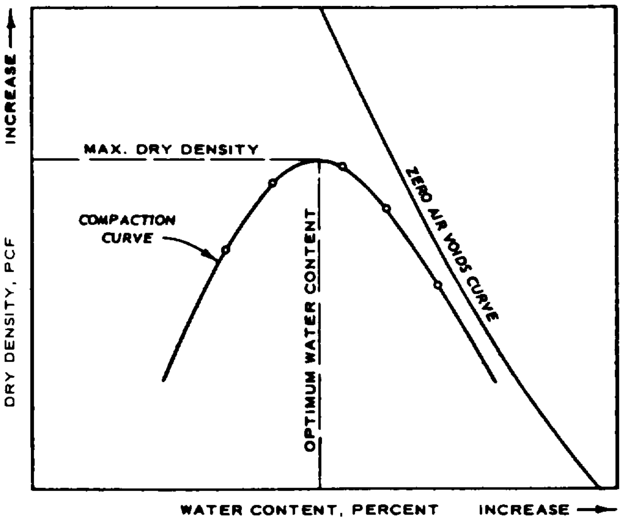

Figure B-1. Compaction curve.

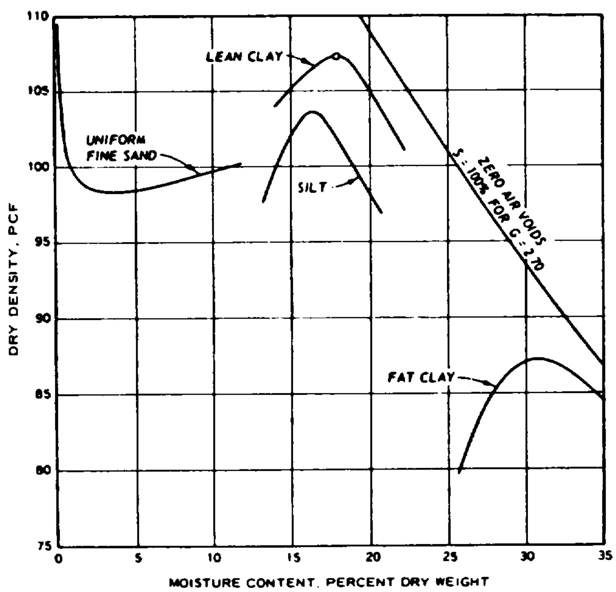

Figure B-2. Typical compaction test curves.

ASTM D 1557 or modified compaction effort, depends on the soil type and varies generally from about 125 to 140 pounds per cubic foot for well-graded, sand-gravel mixtures to about 90 to 115 pounds per cubic foot for fat clays. The optimum water content generally ranges from zero for the sand-gravel mixtures to about 30 percent for the fat clays.

c. Influence of water content. For a given fine-grained soil and a given compaction effort, the water content determines the state at which maximum dry density occurs. At low water contents when the soil is stiff and hard to compress, low, dry densities and high values of air content result. As the water content is increased, higher dry densities and lower air content values are obtained. Increased densities result with an increase in water content up to optimum water content. Beyond this point, the water in the voids becomes excessive, and pore pressures develop under the application of the compaction effort to resist a closer packing; lower dry densities are the result.

d. Influence of compaction effort. For most soils, increasing the energy applied (compaction effort) per unit volume of soil results in an increase in the maximum density (unit weight). This greater density occurs generally at a lower water content. This phenomenon is evident in both field and laboratory compactions. Thus, for each compaction effort, there is a unique optimum water content and maximum dry density for a given soil. Figure B-3 shows the effect of variation in compaction effort on the maximum dry density and optimum water content for a lean clay (CL). Where values of maximum dry density and optimum water content are specified, they should be referenced to the compaction effort used.

e. Influence of lift thickness. Compaction effort applied to a soil surface dissipates with depth. Therefore, it is important that the lift thickness to be compacted be commensurate with the type of soil and the compaction effort. With proper consideration and control over factors influencing compaction, most soils can be compacted to provide a stable backfill, with the

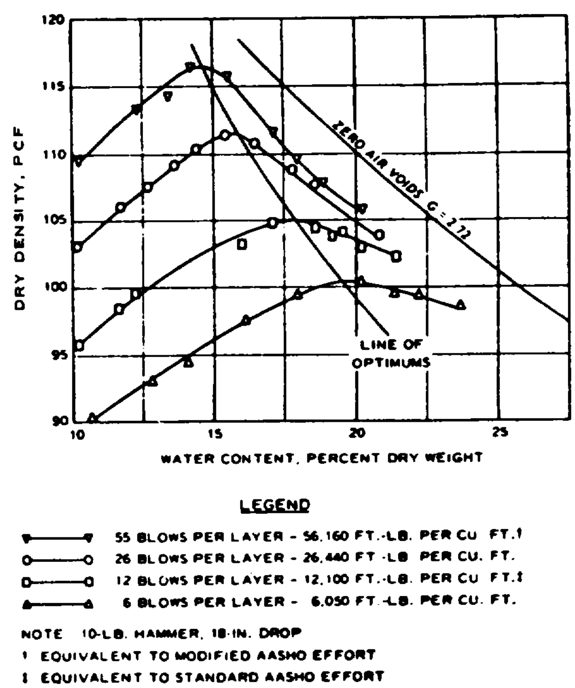

Figure B-3. Molding water content versus density-lean clay (laboratory impact compaction).

exception of certain bouldery soils and soils containing significant amounts of soluble, soft, or organic materials.

B-2. Mechanics of compaction. The influence of the water content on compaction is markedly different on coarse-grained, cohesionless soils and fine-grained, cohesive soils. As a result, the mechanics or manipulation of soil grains in the two types of soil during the compaction process are different. The mechanics of compaction for the two soil types are discussed in subsequent paragraphs.

a. Compaction of coarse-grained soils. Compaction of coarse-grained soils that contain little or no fines and thus exhibit no plasticity (termed cohesionless soils) is achieved by causing the individual particles to move into a closer, more compact arrangement, with smaller particles filling in voids between larger particles. The compaction energy overcomes friction at contact points between particles as they move past one another into closer packing.

(1) A loose volume of coarse-grained soil, such as gravel or sand, contains spaces or "voids" between individual particles that are filled with air and/or water. The density that can be obtained in such a soil under a given amount of compaction effort depends on the gradation and shapes of the particles and on the water content. For a well-graded gravel or sand, the range of particle sizes is sufficient to allow a fairly compact arrangement of particles, with smaller particles filling in the voids between larger particles. For poorly graded soil, either of uniform gradation or skip-graded (lacking a specific range of particle sizes), the distribution of particle sizes limits the density that can be obtained. Segregation of similar size particles in a skip-graded material tends to occur and prevents the voids from being greatly reduced. In a uniform soil, point-to-point contact occurs at very low compaction effort and low density results; further increase in density can only be accomplished by crushing the grains. Therefore, a well-graded, coarse-grained material can generally be compacted to a greater density under a given compaction effort than a poorly graded, coarse-grained soil. The increase in maximum density with increase in compaction effort will be greater for a well-graded soil than that for a poorly graded soil.

(2) Rounded particle shapes facilitate movement and sliding of particles, while angular particle shapes restrict movement and sliding of grains in relation to one another. For either a well-graded, or a poorly graded, coarse-grained material, increase in angularily of grains requires a corresponding increase in compaction effort to obtain a given density. However, a higher density can usually be attained with angular soils because the particle shapes are more conducive to filling the voids.

(3) For coarse-grained soils containing only a small percentage (5 or less) of fine-grained particles, maximum density is more readily obtained when the soil is either dry or saturated. For water contents between these limits, the water in the soil forms menisci between the particle contacts, which tend to hold the soil particles together. This resistance to movement of particles into a more compact structure, termed apparent cohesion or "bulking," results in lower densities than those for either a dry or saturated cohesionless soil under the same compaction effort.

(4) It is to be noted that in the preceding paragraphs, the discussion has centered around the density in weight per unit volume of coarse-grained soils with different gradation characteristics. A more realistic parameter that is often used is the relative density of cohesionless coarse-grained soils. Relative density expresses the degree of compactness of a cohesionless soil with respect to the loosest and the densest conditions of the soil that can be attained by specified laboratory procedures. A soil in the loosest state would have a relative density of zero percent and in the densest state, a relative density of 100 percent. The dry unit weight of a cohesionless soil does not, by itself, reveal how loose or how dense the soil is due to the influence of particle shape and gradation on the density.
Only when viewed against the possible range of variation, in terms of relative density, can the dry unit weight be related to the compaction effort used to place the soil in a backfill or indicate the volume change tendency of the soil when subjected to foundation loads.

(5) Most coarse-grained soils can be compacted to a density such that detrimental additional consolidation will not take place under the prototype loading. This factor is the first important consideration. Another important consideration may be that the compacted soil be sufficiently pervious to provide good drainage. Proper consideration of these two basic factors will allow the use of most coarse-grained soils for backfill purposes.

b. Compaction of fine-grained soils. The mechanics by which fine-grained soils are compacted is quite complex because capillary pressures, hysteresis, pore air pressure, pore water pressure, permeability, surface phenomena, osmotic pressures, and the concepts of effective stress, shear strength, and compressibility are involved. Numerous theories have been developed in an attempt to explain the compaction mechanics. The current state-of-the-art theories involving effective stress give satisfactory explanations. The basic concepts of these theories are discussed below.

(1) Fine-grained soils are compacted in a partially saturated state; therefore, voids or pores contain both pore air and pore water between the soil particles.

Initial compaction water contents below optimum result in initial high pore air pressures and pore water pressures, which reduce shear strength and allow soil particles to slide over one another displacing the pore air to form a more dense mass. This process continues as long as the trapped pore air pressure can escape but requires increasing amounts of compaction effort to achieve higher densities since the soil particles carry increasing amounts of the compaction energy. For a given compaction effort, enough water may eventually be added to the soil so that air channels become discontinuous, and the air is trapped. When the air voids become completely discontinuous, the air permeability of the soil drops to zero; no further densification is possible because at this condition transient pore air pressures can develop that resist the compaction effort. At zero permeability the soil has reached its so-called "optimum water content." Since zero permeability may also be established by closer packing of soil particles, it is evident that lower optimum water contents are possible at higher compaction efforts.

(2) The addition of water above optimum water content causes the voids to become completely filled with trapped pore air and pore water and thereby prevents the soil particles from moving into a more compact arrangement no matter what the compaction effort. Pore water pressure increases significantly with increasing water contents and causes increased reduction in shear strength. This fact is evident in the laboratory compaction mold when the compaction foot sinks deeper and deeper into the soil as water content increases past optimum. The same process occurs in the field when sheepsfoot rollers sink into the soil until the weight is carried by the drum or excessive rutting with rubber-tired rollers

Section B-2. FIELD COMPACTION TEST METHODS

B-3. General. Laboratory test data obtained from laboratory-compacted specimens provide a basis for design, and it is assumed that the engineering characteristics that will be built into the field-compacted backfill will be approximately the same as those of the specimens. Experience has indicated that for most soils, laboratory densities, water contents, and strength characteristics can be satisfactorily reproduced in a field-compacted backfill.

B-4. Field compaction tests.

a. Compaction control tests. Compaction control of soils requires comparison of fill water content and dry density values obtained in field density tests with optimum water content and maximum dry density, or determination of relative density if more appropriate for the fill materials that are cohesionless. For fine-grained or coarse-grained soils with appreciable fines, field results are compared with results of CE 55 laboratory (modified effort) compaction tests performed according to procedures presented in MIL-STD-621A and ASTM D 1557. For free-draining cohesionless soils, relative density of the fill material is determined, if appropriate, using vibratory test procedures prescribed in EM 1110-2-1906 and ASTM D 2049.

b. Frequency compaction control tests. The performance of a standard laboratory compaction test on material from each field density test would give the most accurate relation of the in-place material to optimum water content and maximum density, but this test is not generally feasible to do because testing could not keep pace with the rate of fill placement. However, standard compaction tests should be performed during construction (1) when an insufficient number of the compaction curves were developed during the design phase, (2) when borrow material is obtained from a new source, and (3) when material similar to that being placed has not been tested previously. In any event, laboratory compaction tests should be performed periodically on each type of fill material (preferably 1 test for every 10 field density tests) to check the optimum water content and maximum dry density values being used for correlation with field density test results.

c. Quick field compaction tests. In addition to the standard compaction or relative density tests (para B-2a), at least four relatively quick compaction test methods can provide good approximations of maximum dry density comparable to the standard methods.
The quick compaction methods include: one-point and two-point compaction methods; the Water and Power Resource Service (WPRS), formerly U.S. Bureau of Reclamation (USBR) rapid compaction control method; and for granular cohesionless material, compaction control by gradation. Since only the one-point and two-point methods are currently accepted by the Corps of Engineers for compaction control tests, only these two methods will be discussed in detail. The USBR and gradation methods are briefly summarized.

(1) One-point compaction method. In the one-point compaction method, material from the field density test is allowed to dry with thorough mixing to obtain a uniform water content on the dry side of estimated optimum, and then compacted using the same equipment and procedure used in the five-point standard compaction test. The water content and dry density of the compacted sample are then used to estimate its optimum water content and maximum dry density as illustrated in figure B-4. The line of optimums is

well defined in the figure, and the compaction curves are approximately parallel to each other, consequently, the one-point compaction method could be used with a relatively high degree of confidence. In figure B-5, however, the optimums do not define a line, but a broad band. Also, the compaction curves are not parallel to each other and in several instances cross on the dry side. To illustrate the error that could result from using the one-point method, consider the field density and water content shown by point B in figure B-5. Point B is close to three compaction curves. Consequently, the correct curve cannot be determined from the one point. The estimated maximum dry density and optimum water content could vary from about 92.8 pounds per cubic foot and 26 percent, respectively, to 95.0 pounds per cubic foot and 24 percent, respectively, depending on which curve was used. Therefore, the one-point method should be used only when the basic compaction curves define a relatively good line of optimums.

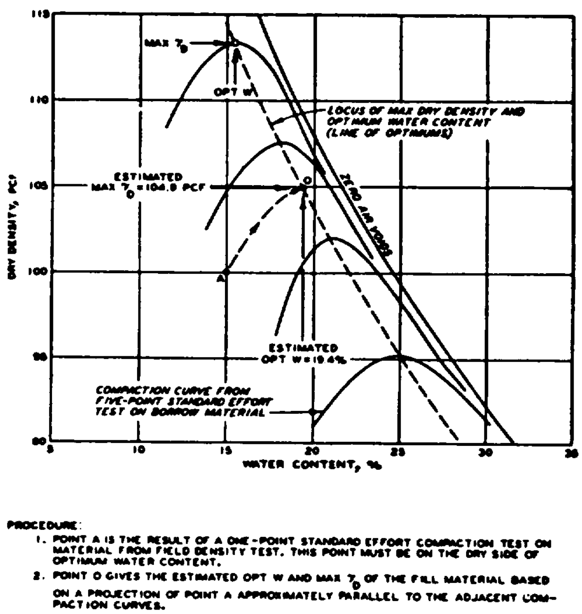

Figure B-4. Illustration of one-point compaction method.

(2) Two-point compaction test results. In the two-point test, one sample of material from the location of the field density test is compacted at the fill water content if thought to be at or on the dry side of optimum water content (otherwise, reduced by drying to this condition) using the same equipment and procedures used in the five-point compaction test. A second sample of material is allowed to dry back about 2 to 3 percentage points dry of the water content of the first sample, and then compacted in the same manner. After compaction, water contents of the two samples are determined by ovendrying or other more rapid means

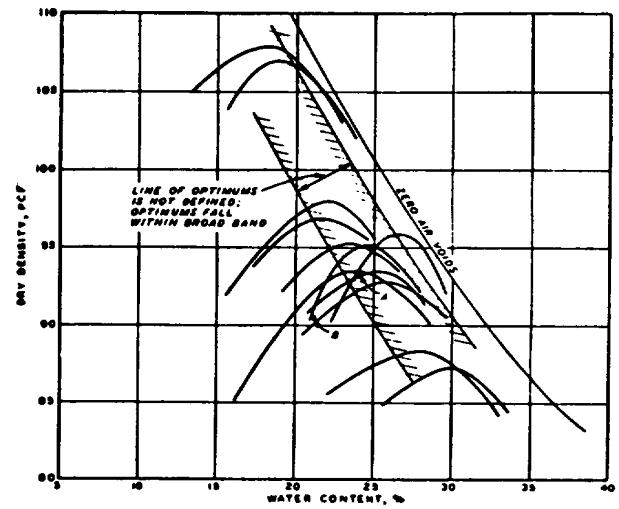

Figure B-5. Illustration of possible error using one- and two-point compaction methods.

(para B-8a), and dry densities are computed. The results are used to identify the appropriate compaction curve for the material test (fig. B-6). The data shown in figure B-6 warrant the use of the two-point compaction test since the five-point compaction curves are not parallel. Using point A only as in the one-point test method would result in appreciable error as the shape of the curve would not be defined. The estimated compaction curve can be more accurately defined by two compaction points as shown. Although the two-point method is more accurate than the one-point method, neither method would have acceptable accuracy when applied to the set of compaction curves shown in figure B-5.

(3) *Rapid one-point test for sands.* A rapid check test for compaction of uniform sands (SP to SM) with less than 10 percent fines (minus No. 200 sieve) is a modified one-point test. The overdry sand is compacted in a 4-inch-diameter mold using CE 55 (modified) effort. Correlation with standard compaction tests is required to confirm the validity of test results for different sands used on each project.

(4) *USBR rapid compaction control method.* Details of this method are described in the USBR Earth Manual (app A). The test is applicable to fine-grained (100 percent minus No. 4 sieve) cohesive soils with liquid limits less than 50. The method, however, is applicable to soils containing oversize particles providing the proper corrections, as stated in EM 1110-2-1911, Appendix B, are applied. It is a faster method than the standard compaction test and is often more accurate than other methods. The method usually requires adding water to or drying back sampled fill material, and thorough mixing is needed to obtain uniform drying or

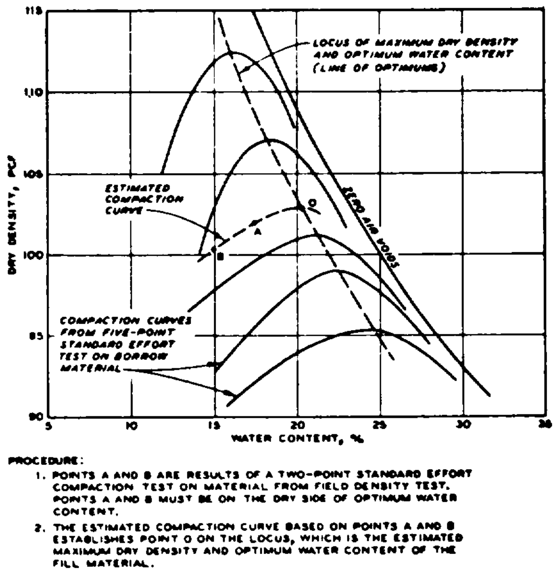

Figure B-6. Illustration of two-point compaction method.

distribution of added water. Otherwise, the results may be erroneous, especially for highly plastic clays. In tough clays, it is likely to be inaccurate because of insufficient curing time for the specimens.

(5*) Grain-size gradation compaction control method*. This test method developed in 1938 is applicable to coarse, medium, and fine-grained sands. The method involves sieve analysis to establish grain-size gradation curves, whose shapes are then correlated with maximum dry density obtained from the standard five-point compaction tests or relative density tests. For a given compaction effort, the maximum dry density of cohesionless material (sand) is also a function of particle shape. Thus, the correlation between grain-size distribution and density would, by necessity, have to include consideration of particle shape. It is doubtful that this method would provide test results more rapidly than the one-point and two-point methods or the relative density method currently accepted by the Corps since samples must be dried for sieve analysis. Therefore, this method is not recommended for routine compaction control.

d. Possible errors. All tests involving mechanical devices and human judgment are subject to errors that could affect the results. In order to properly evaluate test results, the inspector must be familiar with the possible sources of such errors.

(1) *Five-point compaction tests.* The following errors can cause inaccurate results: (a) Aggregations of air-dried soil not completely reduced to finer particles during processing.

(b) Water not thoroughly absorbed into dried material because of insufficient mixing and curing time.

(c) Material reused after compaction.

(d) Insufficient number of tests to define compaction curve accurately.

(e) Improper foundation for mold during compaction.

(f) Incorrect volume or weight of compaction mold.

(g) Incorrect rammer weight and height of fall.

(h) Excessive material extending into the extension collar at the end of compaction.

(i) Improper or insufficient distribution of blows over the soil surface.

(j) Tendency to press the head of the rammer against the specimen before letting the weight fall.

(k) Insufficient drying of sample for water content determination.

(2) One-point and two-point compaction test. The possible sources of errors for the one-point and two-point compaction test are essentially the same as those for the five-point method discussed in (1) above. In addition, appreciable inaccuracy in results may occur for both methods if attempts are made to extrapolate maximum density and optimum water contents from non-uniform families of compaction curves (fig. B-5).

B-5. Field compaction and test sections.

For most soils, laboratory densities, water contents, and strength characteristics can be satisfactorily reproduced in a field-compacted backfill. However, during the initial stage of construction frequent checks of density and water content should be made for comparison with design requirements and adjustments should be made in the field compaction procedure as necessary to ensure adequate compaction.

a. When a compacted backfill is constructed as foundation support for critical structures, or when other requirements, materials, and conditions are unusual, the specifications may provide for the construction of test sections. The test section is used to determine the best procedures for processing, placing, and compacting the materials that will produce compacted backfill having engineering properties compatible with design requirements. Therefore, construction of a test section may involve using different types and different weights of compaction equipment, using different lift thicknesses, using different amounts of compaction applications (different numbers of passes or coverages), processing materials differently with respect to water content control, and mixing to obtain improved gradation. A discussion on test sections for shale materials is presented in Appendix A of FHWA-RD-78-141 and illustrates a wide variation in test results, even for very carefully conducted field tests.

b. By exercising rigid control over the water content, processing, placement, and compaction procedures, by frequent density sampling, by keeping complete records of the procedures and tests, and then by studying and evaluating these records, a procedure to use on the job can be established. In addition to water content and density check tests, undisturbed samples should be obtained to determine that the shear and consolidation characteristics are consistent with design requirements. Once control for field conditions has been established, the backfill can proceed at a normal rate. The contractor should be required to adhere to the established processing, placement, and compaction procedures.

c. If provisions for construction of a test section are not contained in the specifications, the field engineers and inspection personnel should provide maximum guidance to the contractor to aid him in establishing adequate processing, placement, and compaction procedures. To meet this problem the contractor must be provided with suggested improvements of equipment type, if they have not been specified, and procedures during the initial stages of backfill operations. The establishment of the procedures and equipment type that will produce adequate compaction of the backfill material must be supported by a comprehensive program of control testing.

Section B-3. FIELD MOISTURE-DENSITY TEST METHODS

B-6. General. Field density measurements of the compacted backfill are essential to ensure that backfill meets the required design densities necessary for the proper functioning of the structure within that backfill. Although water content requirements are not generally specified in military specifications, the measurement and control of water content is important in obtaining required densities. The four density measurement test methods used for the Corps record and contract acceptance enforcement are listed below.

a. The sand-cone method as described in MIL-STD-621A (Method 106) and ASTM D 1556.

b. The rubber-balloon method as described in ASTM D 2167.

c. The nuclear moisture-density method as described in ASTM D 2922 (for density) and ASTM D 3017 (for water content).

d. The drive-cylinder method as described in MIL-STD-621A (Method 102) and ASTM D 2937 for soft, fine-grained cohesive soils. The water-displacement method described in EM 1110-2-1911, although not currently used for Corps contract enforcement, may be used for supplementary density testing for rocky materials. Rapid field methods of determining or approximating water content-density are also discussed in the following paragraphs.

B-7. Water content and density test methods. Field density can be determined by direct or indirect methods. In the direct methods, the weight of soil removed from a hole and the volume of the hole are determined and used to compute the density. In the indirect methods, a characteristic of the soil, such as radiation scattering or penetration resistance, is measured with an instrument such as a nuclear density meter or penetrometer, and then a previously determined relation between density and the characteristic measured is used to determine the density.

a. Direct methods. The sand-displacement method is considered to be the most reliable direct method and should be used as the standard test by which indirect test results are correlated with density. Other direct methods are the drive-cylinder method, rubber-balloon method, and water-displacement method.

(1) Sand-cone method. Procedures and equipment for the sand-cone method are described in MIL-STD-621A (Method 106) and ASTM D 1556. The procedure as described in the references involves preparation of the ground surface, measurement of an initial volume for the purpose of correcting for surface irregularities, and measurement of a second volume after a small hole is dug. The difference in the volumes is the volume of the hole. The sand used is a standard sand (Ottawa or other sands having rounded grains and a uniform gradation) that has been calibrated for weight versus volume occupied when falling from a standard, constant height. The weight of sand used is measured by weighing the sand density cylinder before and after each volume measurement, and the volume is determined from the weight versus volume calibration. The soil removed from the hole is weighed, the water content determined (MIL-STD-621A), and the dry weight computed. The wet density and dry density of the soil are computed by dividing the appropriate weights by the computed volume. The sand-cone method can be used to determine the in-place density of practically all soils except those containing large quantities of large gravel sizes.

(2) *Drive-cylinder method*. Procedures and equipment for the drive cylinder method are described in detail in MIL-STD-621A (Method 102) and ASTM D 2937. The procedure consists of driving a 3-inch-diameter by 3-inch-high sampling tube of known volume into the soil, excavating the sampling tube and soil, and trimming off the soil protruding from the ends of the tube. The weight and water content of the soil are measured and the dry weight is computed. The wet density and dry density of the soil are computed by dividing the appropriate weights by the computed volume. The drive-cylinder method is limited to moist, fine-grained cohesive soils.

(3) *Rubber-balloon method.* Procedures and equipment for the rubber-balloon method are described in ASTM D 2167. This method utilizes a rubber balloon attached to a glass or metal cylinder containing water and having a scale graduated in cubic feet. An annular device is seated on the prepared ground surface, and the balloon apparatus is placed and held down firmly on the ring. Then water is forced into the balloon under pressures of 2 to 3 pounds per square inch to obtain an initial volume measurement to correct for ground surface irregularities. The apparatus is removed, a small hole is dug, and the apparatus is replaced on the ring. Water is again pumped into the balloon and causes the balloon to conform to the boundary of the hole; then the volume is measured. This volume less the initial volume is the volume of the hole. The volumeter apparatus is simple and easy to operate, and the volume measurement can be made directly and in somewhat less time than that with the sand-cone volume apparatus. The results obtained are considered to be as accurate as those obtained from the sand-cone apparatus. Like the sand-cone method, the rubber-balloon method can be used to determine the in-place density of practically all soils except those containing large quantities of large gravel sizes.

(4) *Water-displacement method.* Where it is necessary to determine the in-place density for a large volume of soil, as in coarse-grained soils containing significant quantities of large gravel sizes, an approximate density can be obtained by excavating a large hole (several cubic feet) and determining the volume by lining the hole with thin plastic sheeting and measuring the quantity of water required to fill the hole. A relatively small sample representative of the material from the excavation is used for determining the water content. Using the wet and dry weights of the material excavated and the measured volume of the hole, the wet and dry densities of the soil can be determined. Although the procedure is not contained in a Military Standard, it is about the only means of determining an approximate density for soils with large sizes of gravel or rock.

b. Size and preparation of test hole. The size of the hole and the care used in preparing the test hole for the sand volume and balloon methods influence the accuracy of the volume measurement. The proper size of the hole is not well established; however, the larger the hole, the less significant small errors in measurement of volume become. The instructions in TM 5-824-2 indicate that a volume of at least 0.05 cubic foot should be used when testing materials with a maximum particle size of 1 inch and that larger volumes should be used for larger maximum particle sizes. ASTM D 1556 suggests certain relations between particle size and the test hole volume and weight of water content specimen. It also recommends increasing the size of the sample used for water content determination with increasing maximum particle size. The relations suggested by the American Society for Testing and Materials are shown in the following tabulation:

Maximum particle size, in.	Minimum test hole volume cu ft	Water content sample g
0.187 (No. 4)	0.025	100
1/2	0.050	250
1	0.075	500
2	0.100	1,000

For significant quantities of larger particles the volumes above should be doubled. The accuracy of the test results is influenced by not only the care taken in preparing a test hole but also the degree of recovery of the excavated material. A hole with irregular surfaces will cause the volume measurement to be less accurate than a hole with smooth surfaces. Thus, the inside of the hole should be kept as free of pockets and sharp projections as possible. Digging a smooth test hole in cohesionless coarse-grained material is particularly difficult. In fine-grained soils without gravel particles, the hole may be bored with an auger, but hand tools will be required to smooth the walls and base of the hole and to recover loose material. For coarser-grained soils and soils containing a significant amount of gravel-size particles, hand tools will generally be required to excavate the hole to prevent disturbing the material in the walls and base of the test hole. Should it become necessary in digging a test hole in highly compacted material to loosen the material by using a chisel and hammer, care must be taken not to disturb the soil around the limits of the hole. All loose particles must be removed after the final depth has been reached, and all particles must be recovered. All soil should be placed in a waterproof container as the soil is taken from the hole. This measure will prevent loss of water before the soil can be weighed.

c. Indirect methods. The indirect methods include use of the nuclear moisture-density apparatus, Proctor penetrometer, and cone penetrometer. Both the Proctor penetrometer and cone penetrometer methods for determining the density require very careful calibration using soils of known density and water content, and considerable experience in operating the device; even so, the accuracy of these methods may be subject to question because of the great influence that non-uniformity of water content or a small piece of gravel can have on the penetration resistance. The Proctor penetrometer may also be used to approximate water content of fine-grained soils.

(1) *Nuclear moisture-density method.* Procedures and equipment for the nuclear moisture-density method are described in ASTM D 2922 (for density) and ASTM D 3017 (for water content). The three methods for determining in-place densities described in ASTM

D 2922 are Method A-Backscatter, Method B-Direct Transmission, and Method C-Air Gap. Of the three methods, Method B-Direct Transmission is recommended over Method A and Method C because it eliminates the effect of vertical density variations.

(*a*) Modern nuclear-moisture density equipment incorporates a radioactive source emitting neutrons and gamma rays and measuring elements (geiger tubes) or "scalers" into a single, self-contained unit. The determination of moisture by the nuclear method is dependent on the modifying of high energy or "fast" neutrons into low energy or "slow" neutrons (ASTM, STP No. 293). Any material containing hydrogen will moderate fast neutrons. Since hydrogen is present primarily in the molecules of free water, the degree of interaction between the fast neutrons and hydrogen atoms represents a measure of the water content of the soil. Density measurements are based on the scattering of gamma rays by the orbital electrons on the atoms comprising the soil. Since the scattering is a function of the electron density, which in turn is approximately proportional to the density of the soil, it is possible to correlate the backscatter of the gamma rays with the soil density.

(*b*) To obtain a water content or density measurement, the appropriate meter is set in place and the voltage setting is adjusted to the correct operating voltage. After the scaler is turned on, a short warmup period (not exceeding 1 minute) is allowed before the test count is started. Intimate contact at the interface between meter and soil is necessary for Method A Backscatter because the scattering of the gamma rays for the density measurement is quite sensitive to even minute air gaps. The normal counting period is 1 minute, with one or two repeat counts taken as a check. Calibration curves for both moisture and density determinations, once the count rates have been established, are furnished by the manufacturers for each individual unit. In general, the calibration curve for moisture determination is more reliable than the curve for density determination. However, it is advisable to correlate both calibration curves on each type of soil with which the instrument is to be used. Such a correlation should be accomplished by using current standard methods for moisture and density determinations or by calibrating on blocks of material of known moisture and density. Examples of calibration for shale materials are given in Appendix A of FHWARD-78-141.

(*c*) For all nuclear-moisture density devices, separate standards are provided so that the count rate can be determined on each instrument at any time in the field. A standard count should be taken three or four times during a day's operation. Although adjustments can generally be made on the instruments so that the count will coincide with the standard count, even a slight adjustment is not usually justified. A more satisfactory procedure is to record the field measurement in terms of percent of this standard count rate, which should be within a reasonable percentage (+ 5) of the given reference count. Use of the percent of standard count, rather than simply the counts per minute, is recommended for increased accuracy. Use of this procedure largely cancels out the effects of such variables as reduction in source strength, background count, and changes in sensitivity of the detector tubes.

(*d*) The calibration curve for the soil being tested is entered with the value of the density meter count rate (taking into consideration the variation from the standard count) to obtain the wet unit weight of the soil. Similarly, the moisture meter yields the weight of water per cubic foot of soil. The unit dry weight of the soil is simply the wet unit weight obtained by the density meter minus the weight of water obtained by the moisture meter. By dividing the water measurement by the dry density, the water content can be expressed in the more familiar terms of percentage of dry weight.

(*e*) Anyone working with nuclear meters must recognize that a possibility of exposure to radiation exists if the safety rules listed by the manufacturer are not followed. When proper procedures and safety rules are followed, the radiation hazard is negligible. For certain instruments, operating personnel must wear a body radiation film badge and carry a pocket dosimeter. These instruments must be ready weekly to ensure that the maximum permissible weekly dosage is less than 100 milliroentgen. Other safety rules deal with handling the devices and being aware of the built-in safety devices. The safety precautions mentioned above may vary or not be applicable for some of the newer devices being manufactured. Therefore, the manufacturer's literature should be carefully studied to determine appropriate safety requirements.

(*f*) It is possible, using nuclear-moisture density apparatus, for one inspector to conduct perhaps 30 water content and 30 density tests per 8-hour working day. The time required per test is only 20 or 25 percent of that required in direct sampling methods. A large number of tests with the nuclear meter correlated with a much smaller number of direct sampling determinations can be of great benefit in ensuring that adequate compaction of the backfill is being obtained. A simple statistical analysis of the data can be made, such as a plot of dry density versus number of tests (ASTM STP No. 293). The resulting bell-shaped curve is a very useful tool since each day's results can easily be added to the plot of previous test results. This procedure can provide an up-to-date picture of the fill densities being obtained and can show the effect of changes made in field compaction procedures.

(2) *Hand cone penetrometer.* The hand cone penetrometer offers a rapid means of checking density requirement of some compacted backfills. The process involves the correlation of penetration resistance with known in-place densities as determined by either the sand-cone or the rubber-balloon method.

(a) Cone penetration resistance is a measurement of soil bearing capacity. Since bearing capacity is dependent on shear strength and thus density, the hand cone penetrometer is an indirect measurement of density. Because shear strength is a function of any pore air and pore water pressures that may be generated by a shearing action of soils containing pore water, the method is applicable only to free-draining materials where pore pressures are dissipated as fast as they are generated. Penetration resistance can also be drastically influenced by the obstruction of gravel size particles. Therefore, the method is applicable only to sands with 100 percent passing the U.S. Standard No. 4 sieve (4.76 mm) and no more than 15 percent passing the U.S. Standard No. 200 sieve (0.074 mm).

(*b*) A plot of hand-cone sounding resistance versus depth of sounding will result in an approximate linear relationship for homogenous materials of relatively constant density for depths of sounding ranging from approximately 2 inches to 20 inches depending on the geometry and size of the cone point and material type. Correlations may be made between known in-place densities and either the angle of inclination between sounding resistance and depth of penetration or the sounding resistance at a given depth. The range of known in-place density must be sufficient to establish a trend between sounding resistance and density. Correlations between density and sounding resistance at a given depth is the simplest correlation since the angle of inclination does not have to be computed. Figure B-7 shows a case example of a correlation between dry density and sounding resistance measured at 6 inches below the surface. Contract specification required a minimum acceptable dry density of 104.7 pounds per cubic foot (98 percent of the maximum dry density according to the compaction method described in ASTM D 1557). Figure B-7 also indicates that all soundings with resistances of 110 pounds or more corresponded to densities greater than 104.6 pounds per cubic foot. Therefore, no additional standard density checks are needed beyond the routine tests. When all soundings with resistance of 86 pounds and below correspond to densities below 104.6 pounds per cubic foot, it is evident that sufficient compaction has not been achieved and additional standard density checks are definitely needed for an acceptance or rejection decision. Sounding with resistances between 86 and 110 pounds may or may not need additional density checks depending on whether the inspector has reason to suspect adequate compaction has or has not been achieved.

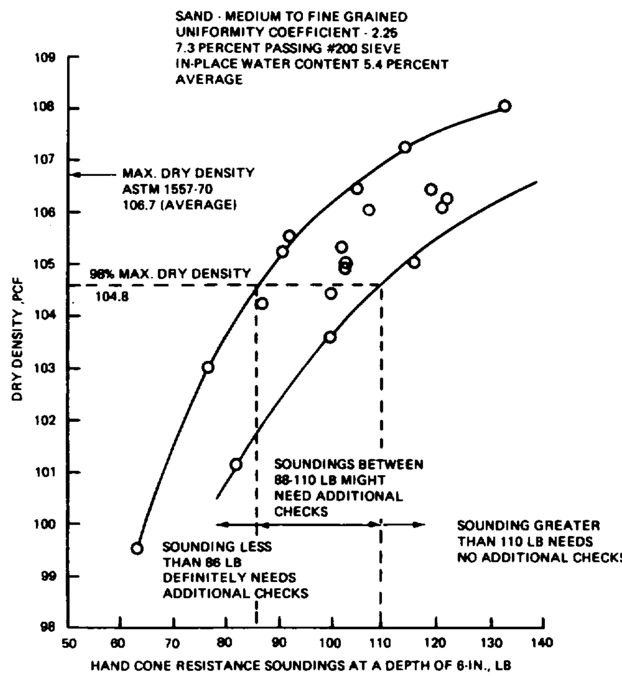

Figure B-7. Correlation between dry density and hand cone resistance at a depth of 6 inches below the surface.

(*c*) The correlation between sounding resistance and known in-place dry densities (fig. B-7) is made directly without knowing water content at each sounding location. Although sounding resistances are affected by water content for the dry, moist, and 1 to 2 percentage points above optimum state, the range of possible water content in the moist state does not significantly affect sounding resistance.

(*d*) The hand cone penetrometer is ideally suited for use in confined zones where sand is used as backfill and where rapid control aids are needed to determine if adequate compaction has been achieved. With a little practice, a hand-cone sounding can be made in less than 1 minute.

d. Possible sources of errors. Since the decision to accept or reject a particular part of a backfill is primarily dependent upon the results of in-place density control tests, it is important for the inspector to be familiar with the possible sources of errors that might cause an inaccurate test result. Some of the more likely sources of errors for the sand-cone, rubber-balloon, and nuclear moisture-density methods are discussed below. All tests that are suspected to be in error must be repeated.

(1) *Sand-cone method.* The major sources of possible error are as follows: (a) The sand-cone method relates the bulk density of a standard sand to the known weight of the

same sand occupying an in-place volume of sampled material. Changes in effective gradation between or within batches of sand may significantly affect the test results. This error can be minimized by frequent calibration of the sand's bulk density.

(*b*) Loose sand increases in density when subjected to vibrations. Care must be taken not to jar the sand container while calibrating bulk density in the laboratory or during in-place volume measurements in the field. A common error is to use the sand cone method for in-place volume measurements adjacent to the operation of heavy equipment. Heavy equipment can generate vibrations that densify the sand and result in erroneously high-volume measurements and low in-place densities.

(*c*) Appreciable time intervals between bulk density determination of the sand and its use in the field may result in change in the bulk density caused by a change in the moisture content of the sand.

(2) *Rubber-balloon method*. The major sources of possible error are as follows: (a) New rubber-balloon volumeters should be calibrated against several known volumes of different sizes covering the volume range of in-place measurements.

(*b*) For stiff soils such as clay, it is possible to trap air between the sides of the sample hole and balloon. This error can be minimized by placing lengths of small-diameter string over the edge of the hole and down the inside wall slightly beyond the bottom center.

(*c*) The application of the 2- to 3-pounds-per-square-inch pressure to extend the balloon into existing irregularities in the hole will cause a noticeable upward force on the volumeter. Care must be taken to ensure that the volumeter remains in intimate contact with the base plate.

(*d*) The rubber balloon must be frequently checked for leaks.

(3) *Nuclear moisture-density method*. The major sources of possible error are as follows:

(*a*) The single consistent source of error is related to the accuracy of the system. The overall system accuracy in determining densities is statistical in nature and appears to vary with the equipment used, test conditions, materials tested, and operators. If proper procedures are followed, the standard deviations in terms of accuracy will vary on the order of 3 to 5 pounds per cubic foot for density tests and 0.5 to 1.0 pound of water per cubic foot of material for water content tests.

(*b*) Manufacturers furnish calibration curves for each piece of equipment. Due to the effects of differing chemical compositions, calibration curves may not be applicable to materials not represented in establishing the calibration curve. Apparent variations in calibration curves may also be induced by differences in the seating, background count, sample heterogeneity and surface texture of the material being tested.

B-8. Rapid field water content control procedures. In many cases, particularly in confined zones, it is important to rapidly determine the dry density of a given part of the backfill in order to prevent the possibility of costly tear out and rebuild operations. The test procedures for determining dry densities using the sand-cone and rubber-balloon methods sometimes require extensive drying times (depend on material type up to 16 hours) to determine water content. Alternate techniques for rapidly determining water content are discussed below.

a. Microwave ovens. Microwave energy may be used to dry soil rapidly and thus enable quick determination of water content (ASTM STP No. 599). However, in drying soils with microwaves, the only control on the amount of energy absorbed by the soil is exposure time; consequently, if soils are left in the oven too long, severe overheating can occur. This overheating of the soil can cause bound water, a part of the soil structure, to be driven off and thus result in significant errors in water content measurements. In addition, continuous heating can result in excessive heat being generated; certain soils have been observed to fuse or explode and thereby create hazards to both equipment and personnel.

(1) Times required for drying in a microwave oven are primarily governed by the mass of water present and the power-load output of the oven, as expressed by

$$GT = \frac{M_w[(0.2/w + 1)(100 - t_o) + 539](4.18896)}{P} \quad (B-1)$$

where

T = time in the microwave oven, seconds

M_W = mass of water present in the soil-water mixture, grams

w = water content of the specimen

t_o = initial temperature of the soil-water mass, degree Centigrade

P = power output of the oven, watts

This governing equation indicates that in order to predict accurately the drying times required, an estimate of the specimen water content must be made and the oven power versus load relationship must be established by calibration.

(2) The limitation of having to estimate the initial water content of the specimen is not insurmountable. Test results indicate that slight overestimations of the actual water content, i.e., longer drying times, generally result in small differences between conventional oven and microwave oven water contents. Conversely, underestimations of water content result in more serious errors. If an accurate estimate of water content

cannot be made, experience has shown that close visual observation often can be used to determine if soil overheating is occurring. An alternative approach is to incrementally dry a duplicate specimen until a constant weight is obtained, calculate the water content, and input this value into equation (B- 1).

(3) The useful power output "P" is determined in the laboratory by subjecting a mass of distilled water to microwaves for a given time and then measuring the rise in temperature induced in the water. Power in watts is calculated from

$$P = \frac{M_w t}{Tc} \; 4.18896 \qquad \text{(B-2)}$$

where

MW = mass of distilled water in the oven, grams

t = increase in temperature of the distilled water, degree Centigrade

T_c, = time in the oven for calibration, seconds

A plot is then made of power output and oven load (mass of water in oven) in grams of water as shown in figure B-8.

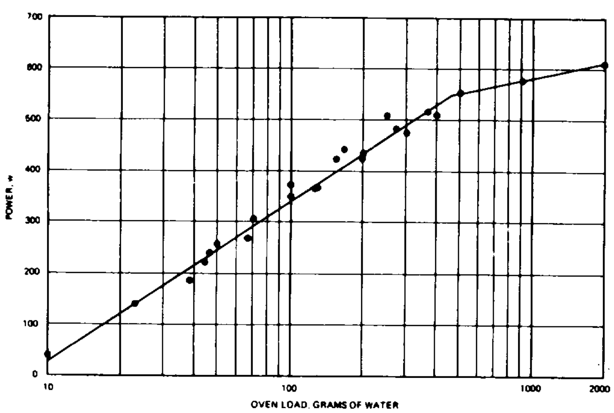

Figure B-8. Power Applied by the Oven to Dry Moist Soils.

(4) The water content estimate is used to calculate the mass of water in the specimen from

$$MW = \frac{(Wwet)\,(W)}{(1 + w)} \qquad \text{(B-3)}$$

where

M_W = mass of the water in the specimen, and equivalent to oven load in figure B-8, grams

Ww,t = wet weight of the specimen, grams

By calculating M_W (oven load in fig. B-8) from equation (B-3) and finding a comparable value of power from a plot similar to figure B-8 for the particular oven used, the drying time may be calculated from equation (B-1).

(5) It may not be possible to successfully dry certain soils in the microwave oven. Gypsum may decompose and dehydrate under microwave excitation. Highly metallic soils (iron ore, aluminum rich soils, and bauxite) have a high affinity for microwave energy and overheat rapidly after all the free water has been vaporized. Hence, extreme care is required when drying these soils. For the same reason, metallic tare cans or aluminum plates are not permissible as specimen containers.

(6) Because microwaves are a type of radiation, normal safety precautions to avoid undue exposure should be observed.

b. Proctor penetrometer. The Proctor penetration resistance method in the hands of inspection personnel experienced in its use provides a rapid expedient check on whether the field water content is adequate for proper compaction. However, the method is suitable only for fine-grained soils because coarse sand or gravel may cause erroneously high resistance readings. The method consists of compacting by the procedure used for control of a representative sample of soil taken from the loose lift being placed. The compacted specimen is weighed, and the wet unit weight is determined. The penetration resistance of the compacted specimen in the mold is then measured with the soil penetrometer. The moisture content can then be estimated by comparing the penetration resistance of field compacted specimens with a relation previously established in the laboratory between wet unit weight, penetration resistance, and moisture content. The procedure requires about 10 minutes and is sufficiently accurate for most field purposes. The procedure to determine the relation between wet unit weight, penetration resistance, and moisture content is described in ASTM D 1558. The relation is generally developed in conjunction with the compaction test.

c. Other methods. Other methods for determining water content include drying by hot plate or open flame, drying by forced hot air and a rapid moisture test that uses calcium carbonate. In the hot plate method, a small tin pan and a hot plate, oil burner, or gas burner (something to furnish fast heat) are used. A sample of wet soil is weighed, dried by one of the above mentioned methods, and weighed again to determine how much water was in the sample. This method is fast, but care must be taken to ensure that the material is thoroughly dry. Also, if both organic matter and bound water are removed, higher water content determinations than those obtained by ovendrying sometimes result. In the forced hot air, a sample is placed in a commercially available apparatus containing an electric heater and blower. Hot air at 150 to 300 degrees Fahrenheit is blown over and around the sample for a preset time. A 110- or 230-volt source is required. Available sizes of apparatus can accommodate sample weights from 25 to 500 grams. Drying times are estimated to vary from 5 minutes for sand to as long as 30 minutes for fat clay. The rapid moisture test and limitations are described in STP 479.